3.0 TECHNICAL APPROACH

3.1 DATA SOURCES

Data sources included 12 months of field investigations by the project proponent, including installation of eight monitor wells in multiple aquifers, four geologic test holes, aquifer testing, monitoring of water levels and spring flow rates, isotope sampling, vegetation mapping, and water balance preparation. Other basin-specific data included an assessment of the basin water resources by USGS (Davidson 1973), spring mapping and Big Sandy River flow measurements by BLM, geologic and water level information from the Arizona Department of Water Resources (ADWR) well database, and river flow data from USGS. In addition, many references (some listed in Section 6.0 and others referenced in other documents related to this project) were also used in understanding and defining flow patterns, volumes, and behavior in the Big Sandy basin. Specific references are cited at the point where the data are used in the present report.

3.2 CONCEPTUAL MODEL

The purpose of this section is to summarize the conceptual model (data and assumptions) that form the basis of the Big Sandy model and its conclusions. The parts of the conceptual model described here follow the list provided in EPA's assessment framework for groundwater model applications (EPA 1992). The main topics covered are the hydrogeologic system (including aquifer system, hydrologic boundaries, and hydraulic properties), sources and sinks, water balance, data gaps, and boundary conditions. The model construction section summarizes data supplied to the model and boundary conditions.

Hydrogeologic System

The Big Sandy basin covers an area of approximately 800 square miles in southeastern Mohave County, Arizona (Figure 1). Groundwater within the basin originates as natural precipitation, which supplies water to the regional aquifer through recharge in stream channels and along the mountain fronts. In general, groundwater flows from the mountains toward the center of the basin, then south parallel to the Big Sandy River (Cady 1981; Davidson 1973;). Details of groundwater sources and sinks are given in the water budget (Section 3.2.3).

North of Wikieup, the Big Sandy River is ephemeral, flowing only in response to direct precipitation. Near Wikieup, the river becomes perennial for approximately 6 miles before disappearing underground about 1.5 miles upstream of Granite Gorge. This perennial reach may be due in part to the presence of a lacustrine deposit, or "lakebed clay," that occurs in the southernmost part of the basin. The lacustrine deposit, which is believed to function as an aquitard, may force groundwater to the surface, where it provides base flow to the river. Perennial flow reappears near the southern boundary of the basin, at the end of the marsh, and continues south through Granite Gorge. Groundwater also exits the basin as underflow in the Big Sandy River channel at Granite Gorge.

During the field program, the project proponent identified a very shallow clay layer within the perennial segment of the river (Manera 2000). It has been postulated by the project proponent that this clay layer may also provide a mechanism for sustaining perennial flow in the river, and hydraulically separating surface flow from groundwater.

Aquifer System. Subsurface lithologic data obtained from drilling at the proposed power plant site, and logs from U.S. Department of Energy (DOE) wells (Lease 1981), indicate that there are five hydrogeologic units in the southernmost part of the basin: (1) arkosic gravel at depth beneath most of the basin, (2) a volcanic lower aquifer (also referred to as the volcanic aquifer), which is confined and under a substantial amount of artesian pressure; (3) a middle aquifer composed of conglomerate (lower basin fill) and which is also confined; (4) a lacustrine deposit (lakebed clay) which serves as an aquitard to the middle aquifer, and (5) an upper aquifer which includes the recent alluvial deposits of the Big Sandy River (upper basin fill). The volcanic aquifer pressures are maintained by an aquitard surrounding the aquifer. Although almost all of the subsurface data are concentrated in the vicinity of the power plant site, the areal extents of these units were extrapolated using subsurface lithologic data from the six deep exploration wells logged by DOE (Lease 1981).

The water-bearing portion of the upper aquifer forms a narrow band along the floodplain of the Big Sandy River, and spans the entire length of the basin. The lacustrine deposit crops out along the banks of the Big Sandy River in the southernmost part of the basin but disappears into the subsurface north of Wikieup, where it is thought to grade into coarser-grained basin-fill deposits (Figure 2). The middle aquifer is probably laterally connected with other units throughout the basin.

The extent and depth of the lower aquifer is not precisely known; however, because this volcanic unit is connected to the volcanic mass that composes the southern portion of the Aquarius Mountains, which appears to be the source of the volcanic material, it is inferred to be restricted to the southern portion of the Big Sandy basin. The arkosic gravel is also not well-defined due to a lack of subsurface data, but is believed to be present beneath most of the lower aquifer.

The results of isotope testing of waters from the upper and lower aquifers and springs in the Aquarius Mountains as well as the Hualapai Mountains to the north indicated that the lower aquifer is hydraulically connected to, and receives recharge mainly from, the Aquarius Mountain volcanics to the east. The upper aquifer was shown to receive part of its recharge from a higher elevation source, such as the Hualapai Mountains and/or Cottonwood Mountains at the northern end of the Big Sandy basin.

Hydraulic Boundaries. Hydraulic boundaries include the surface water divides on the east, north, and west sides of the basin, and the hydraulic barrier created by a volcanic plug blocking the southern part of the basin. The boundaries of the groundwater system fall inside these hydraulic divides; the edge of the continuously saturated zone generally coincides with the margins of the basin where mountain front recharge sustains groundwater flow.

Hydraulic Properties. Hydraulic properties for most of the hydraulic units were based on aquifer tests in the alluvium, and well yields in the other units (Davidson 1973). Hydraulic properties for the lower (volcanic) aquifer were based on the results of the aquifer test of that unit performed by the project proponent (David Schafer & Associates 2001). Literature data were used to supplement field measurements. In addition, model calibration to observed heads, the aquifer pumping test, and the derived water balance for the basin were used to revise some hydraulic properties.

Details of the hydraulic property ranges, their sources, and the values supplied to the model are provided in Section 3.4.2.

Sources and Sinks

Sources and sinks to groundwater are described below and quantified in the water budget (Section 3.2.3).

INFLOW

Sources of inflow (recharge) to the Big Sandy basin can be classified as either incidental (anthropogenic) recharge or natural recharge.

Incidental Recharge

Sources of incidental recharge to the Big Sandy basin include agricultural irrigation, livestock watering, and domestic use. Estimates of incidental recharge for these three sources were obtained from the Big Sandy 1990 Water Use Report (USGS 2000).

Agricultural Irrigation. USGS derived recharge from agricultural irrigation by estimating groundwater withdrawals and surface water diversions for agricultural use, and subtracting the total consumptive use. The total consumptive use was derived from the total irrigated acreage and the average consumptive use based on the types of crops grown. The total estimated annual recharge from agricultural irrigation is 22 acre-feet, or 0.1 percent of total basin inflow.

Livestock Watering. Recharge from watering of livestock was derived by estimating groundwater withdrawals and surface water diversions to supply livestock tanks (typically earthen impoundments and subtracting the total consumptive use. The total consumptive use presumably includes evaporation and livestock use. The total estimated annual recharge from livestock watering is 45 ac-ft, or 0.2 percent of total basin inflow.

Domestic Use. Recharge from domestic use was derived using groundwater withdrawals from both public and private wells, and subtracting the total consumptive use. The total consumptive use was derived from the total population of the Big Sandy area, and an average per capita consumptive use factor. The total estimated annual recharge from domestic use is 45 ac-ft, or 0.2 percent of total basin inflow. It is assumed that most of the unused water is recharged through septic systems.

Natural Recharge

Natural recharge in an alluvial basin includes mountain front recharge, stream channel recharge, and recharge from direct precipitation. For this water budget, groundwater underflow entering the Big Sandy basin from the Hackberry Sub-Area to the north (Remick 1981) also was included as natural recharge. Of the two general categories of recharge, natural recharge is always the most difficult to estimate due to the infeasibility of making direct measurements, and the wide range of estimates obtained using various analytical methods (Wilson et. al. 1980). Because of this, natural recharge was not estimated using empirical methods, but rather, was calculated to balance the water budget. The calculated value for natural recharge obtained using this approach is 26,194 acre-feet per year (ac-ft/yr), or about 99.6 percent of total basin inflow.

To substantiate this calculated value, an approximate estimate of natural recharge was made using the Maxey-Eakin method, which assumes that the total percentage of precipitation that is recharged increases with precipitation (Wilson et. al. 1980, p. 4-35). The normal annual precipitation in the Big Sandy area ranges from 10 to 14 inches (Davidson 1973). Assuming an annual average precipitation of 12 inches (1 foot) and a total basin area of 700 square miles (448,000 acres), the total annual precipitation would be about 448,000 ac-ft. According to the Maxey-Eakin method, approximately 5 percent (22,400 ac-ft) of this volume would be recharged

(Wilson et. al. 1980, p. 4-36). This value compares favorably with the 26,194 ac-ft value obtained from the water budget calculation.

OUTFLOW

Sources of outflow (discharge) include groundwater pumpage, evapotranspiration, evaporation and evapotranspiration at the marsh near the Denton well, Cofer Hot Spring Flow, consumptive use of surface water for irrigation, and outflow at Granite Gorge.

Groundwater Pumpage

Sources of groundwater pumpage include pumpage for agricultural irrigation, livestock watering, domestic use, and mining. Estimates of groundwater pumpage for these four sources were obtained from the Big Sandy 1990 Water Use Report (USGS 2000).

Agricultural Irrigation. Pumpage estimates for agricultural irrigation were derived by USGS from electrical power company records. Kilowatt hours were converted to gallons per minute (gpm) pumped based on the depth to groundwater and an average pump efficiency. The total estimated pumpage to support agricultural irrigation is 34 ac-ft, or 0.1 percent of total basin outflow.

Livestock Watering. Pumpage estimates for livestock watering irrigation were derived from electrical power company records, using the same method employed to estimate agricultural irrigation pumpage. The total estimated pumpage to support livestock watering is 123 ac-ft, or 0.5 percent of total basin outflow.

Domestic Use. Pumpage estimates for public (municipal supply) wells were obtained from water company delivery records. For privately owned wells, pumpage was estimated based on the estimated population that receives water from domestic wells, and an average per capita total water use factor. The total estimated pumpage for domestic use is 101 ac-ft, or 0.4 percent of total basin outflow.

Mining. This category of pumpage refers solely to groundwater pumped to supply the Phelps Dodge Bagdad mine, located approximately 20 miles east-southeast of the Big Sandy basin. The pumpage estimate for the Bagdad mine was derived by USGS based on the amount of copper produced in 1990, and a water consumption factor for the mine based on the methods used to extract copper from the ore. The total estimated pumpage for the Bagdad Mine in 1990 is 2,005 ac-ft, or 7.6 percent of total basin outflow.

Evapotranspiration

Evapotranspiration for this water budget refers solely to water use by riparian vegetation (phreatophytes). Evapotranspiration estimates in the water budget developed by Davidson (1973) were updated by obtaining the total riparian acreage from a geographic information system (GIS) land use cover, if available, and applying an average consumptive use factor based on the relative percentages of riparian plant types. Areas of dense riparian vegetation occur along the Big Sandy River, Deluge Wash, and Cane Springs Wash. The density of riparian vegetation is greatest along the Big Sandy River, particularly along the perennial reach of the river in the vicinity and south of Wikieup. The riparian vegetation is primarily a mix of mesquite and saltcedar with small sections of cottonwood. Davidson's evapotranspiration estimates were developed by compiling areas of riparian vegetation from topographic maps based on aerial photographs, and field-checking each area. Vegetation density was estimated from aerial photographs taken in 1954. The total area covered by riparian vegetation, adjusted to 100 percent density, was estimated to be 4,600 acres. Assuming a consumptive use factor of 4 ft per year, the loss of water to evapotranspiration is estimated to be 18,400 ac-ft/yr (Davidson 1973, p. 36), or 70.0 percent of total basin outflow. These evapotranspiration estimates were updated for the southern half of the basin based on recent vegetation mapping, and literature for consumptive use.

Evaporation and Evapotranspiration at Marsh Near Denton Well

The marsh at the southern end of the basin, about 1 mile upstream from Granite Gorge, creates outflow from the basin through evaporation, evapotranspiration and surface flow to the downstream perennial reach of the Big Sandy River. The area of the marsh is estimated to be 335 acres based on the extent of vegetation shown on the USGS quadrangle of the area, then given an evaporation rate of about 95 inches/year (Trauger 1972) and a crop coefficient of 1.12 based on a 50/50 mixture of reed swamp and shallow standing water (FAO website 2001) the calculated outflow at the marsh is 3,053 ac-ft/y or 11.6 percent of the total basin outflow.

Cofer Hot Spring Flow

The flow rate at Cofer Hot Spring was measured at 176 gpm, or 290 ac-ft/yr (Caithness 2000), or 1.1 percent of total basin outflow. Flow rates at other springs in the area, which amount to less than 7 gpm,were later determined to be flowing in perched flow systems separate from the valley aquifers, and therefore were not accounted for in the basin water budget.

Consumptive Use of Surface Water for Irrigation

Surface water for agricultural irrigation is supplied to the Banegas Ranch from the Big Sandy River through an upstream diversion structure. The annual consumptive use and evaporative loss of surface water due to agricultural operations at Banegas Ranch is estimated to be 300 ac-ft/yr, or 1.1 percent of the total basin outflow. Surface water diversions for other parcels of agricultural land in the basin have not been identified.

Outflow at Granite Gorge

The total volume of water that exits the basin as outflow at Granite Gorge includes groundwater underflow in the river alluvium and surface water flow in the Big Sandy River. The amount of groundwater leaving the Big Sandy basin as underflow at Granite Gorge was estimated by Davidson (1973) to be approximately 800 ac-ft/yr, assuming a hydraulic conductivity of 1,000 ft per day, a saturated cross-sectional area of 9,000 square ft, and a hydraulic gradient of 0.01 feet per foot (ft/ft). Perennial flow in the Big Sandy River at the northern end of Granite Gorge has not been measured. However, the BLM has measured flows in the river about 1 mile downstream of the northern end of the gorge. The average annual flow of the Big Sandy River, based on the BLM measurements, is 3,280 ac-ft/yr. These flow measurements may include storm flows as well as base flow.

The estimated range of outflow at Granite Gorge for the water budget, based on the Big Sandy flow measurements downstream of the gorge and the underflow estimates made by the USGS, was the average value of 2,000 ac-ft/yr , or about 7.6 percent of the basin outflow.

Water Budget

This section presents a water budget for the Big Sandy basin for current conditions. The water budget (inflow – outflow +/- change in storage = 0) has been developed to evaluate the relative significance of various sources of groundwater recharge and discharge, and to assist in developing a conceptual hydrogeologic model of the basin. The water budget also is the initial step in the construction of the groundwater flow model of the site. The water budget is summarized in Table 1.

All of the data used to develop the water budget were obtained from publicly available sources. The water budget developed by Davidson (1973) for the Big Sandy basin was used as a starting point for the current water budget. Although the information used by Davidson to develop that water budget is now 30 years old, Davidson's values for one component, underflow at Granite Gorge, was incorporated into the current water budget. Data for incidental recharge and groundwater pumping were obtained from the USGS Internet site (USGS 2000).

Change in groundwater storage was evaluated by reviewing water level data from several index wells in the Big Sandy basin. Index wells are wells with long periods of record that typically are measured annually by ADWR or USGS. A review of water level data from these wells revealed no long-term changes in water level elevations, only short-term fluctuations. Based on the results of this review, it was concluded that there is no long-term change in storage in the basin.

The water budget for the Big Sandy basin presented in this report indicates that the two largest components of the water budget, natural recharge and evapotranspiration, probably are the most uncertain. Natural recharge estimates derived using one or more accepted methods probably would not yield conclusive results. The water budget also indicates that the Phelps Dodge Bagdad mine, as expected, is by far the largest groundwater user in the basin. The water budget could be improved by obtaining current estimates of mine pumpage.

Data Gaps

The following data gaps were identified when creating the conceptual model:

- recharge rate into the volcanic outcrop area
- specific yield of the volcanic aquifer
- hydraulic properties of the aquitard units
- extent of the volcanic aquifer near Granite Gorge

Each of these data gaps was discussed in hydrology team meetings. Relevant parts of the discussions are reported below.

Recharge Rate Into Volcanic Outcrop

The estimated recharge rate into the volcanics was discussed in a hydrology team meeting prior to modeling analyses. A quote from the meeting minutes follows:

The 10 percent recharge value suggested by the water resources report (Caithness, 2000) is only for direct precipitation on highly fractured basalt of the recharge area. No other recharge was considered. Flow out of Cofer Hot Spring (initially reported by Caithness to be 350 gpm) constitutes almost half of the 865 gpm proposed recharge. The water presently issuing from Cofer Hot Spring is being used by the property owner. Other area springs mapped and measured by BLM have a total flow of less than 25 gpm. Where the remainder of the recharged water goes is not known.

As a result of various analyses and measurements, the following issues raised in the hydrology team meeting were subsequently resolved:

(1) The flow out of Cofer Hot Spring was measured by Paul Manera of Manera, Inc. and was estimated to be 176 gpm.

(2) The recharge rates basin-wide were estimated to be 5 percent of precipitation based on application of the Maxey-Eakin method for the appropriate elevation. This rate of recharge agreed well with the water budget for the basin (Section 3.2.3). This recharge is distributed unevenly over the basin. The greatest recharge occurs along the mountain fronts as a result of runoff from the uplands. In addition, a higher than average fraction of recharge is expected in the area of the volcanic outcrop, which is fractured and at a higher elevation than the surrounding terrain. Volcanic outcrop recharge rates varying from 0.75 to 1.85 inches per year (in/yr) (6 to 15 percent of precipitation) were tested in the model. The water recharging the volcanic outcrop is believed to discharge via Cofer Hot Spring and into the aquifers surrounding the volcanic aquifer. The distribution of this discharge is unknown and was modeled as a function of the predicted head differences and assumed hydraulic conductivities of the adjacent layers. These hydraulic properties were varied in the model sensitivity analyses (Section 3.6).

TABLE 1
BIG SANDY BASIN WATER BUDGET FOR CURRENT CONDITIONS

Water Budget Component	Annual Volume (ac-ft/yr)	Percent of Total Inflow/ Outflow	Source of Data/Comments
Inflow			
Incidental Recharge			Source: Big Sandy 1990 Water Use Report (USGS Web Site).
Agricultural Irrigation	22	0.1	Includes conveyance losses and infiltration.
Livestock Watering	45	0.2	Stock pond infiltration.
Domestic Use	45	0.2	Recharge primarily from septic systems.
Subtotal Incidental Recharge	112	0.4	
Natural Recharge	26,194	99.6	Calculated balance of inflow (assuming no change in storage).
Total Inflow	**26,306**	100.0	
Outflow			
Groundwater Pumpage			Source: Big Sandy 1990 Water Use Report (USGS Web Site).
Agricultural Irrigation	34	0.1	Estimated from electrical power company records.
Livestock Watering	123	0.5	Estimated from electrical power company records.
Domestic Use	101	0.4	Public pumpage from delivery records, private pumpage from gpcd
Mining	2,005	7.6	Phelps Dodge Bagdad Mine, based on mine production.
Subtotal Groundwater Pumpage	2,263	8.6	
Evapotranspiration	18,400	70.0	Davidson 1973, p. 36, based on 4 ft/yr x 4,600 acres (8,500 – 16,300 ac-ft/yr in southern half of basin, based on updated acreages and vegetation types).
Evaporation and Evapotranspiration at Marsh Near Denton Well	3,053	11.6	335 ac vegetation area (USGS Quad. Map)
Cofer Hot Spring Flow	290	1.1	Caithness (2000)
Consumptive Use of Surface Water for Irrigation	300	1.1	Based on the consumptive use and evaporative losses due to agricultural operations at Banegas Ranch.
Outflow at Granite Gorge	2,000	7.6	Outflow may range from 800 ac-ft/yr (Davidson 1973, p. 37) to 3,280 ac-ft/yr (BLM measurement at site B1, segment C, below Granite Gorge)
Total Outflow	**26,306**	100.0	
Change in Storage	**0**		No change in storage, based on analysis of long-term water level data.

Specific Yield of the Volcanic Aquifer

Specific yield data for the lower (volcanic) aquifer could not be derived from the aquifer pumping test. Literature data for fractured or vesicular basalt, bracketing the observed hydraulic conductivity of about 50 ft per day (ft/d) from the aquifer pumping test, gave the following ranges of values:

- Singhal and Gupta (2000): 10 to 17 percent porosity for hydraulic conductivities ranging from 2.8 x 10^{-4} to 283 ft/d

- Trauger (1972): 4 to 9 percent specific yield (5 to 10 percent porosity) for hydraulic conductivities ranging from 5 to 500 ft/d

During a hydrology team meeting, Paul Manera of Manera, Inc. mentioned that the volcanic aquifer cores were somewhat vesicular and somewhat fractured and showed deposition of malachite, evidence of well-connected fractures. He also concluded that specific yields were likely to be in the range of 8 to 13 percent.

It was concluded and agreed that a range of 7 to 15 percent specific yield for the volcanic aquifer would be modeled, with a best-estimate value of 11 percent.

Hydraulic Properties of the Aquitard Units

Hydraulic conductivities of the aquitards were discussed during a hydrology meeting and a range of 1 x 10^{-4} to 1 x 10^{-6} ft/d was agreed to be tested in the model.

Extent of Volcanic Aquifer Near Granite Gorge

The extent of the volcanic aquifer in the vicinity of Granite Gorge was discussed in a hydrology team meeting. The potential installation of a middle aquifer monitor well was discussed, as follows:

- Paul Summers (BLM) inquired about the feasibility of installing a monitor well in the middle aquifer near Granite Gorge to determine leakage from lower aquifer into the middle aquifer. The borehole would also provide lithologic data.

- Potential problems with this include: (1) distance from the pumping well (4 miles) may preclude relevance to assessing impacts from pumping, (2) the high cost ($55,000 to $60,000 for an 800-ft well and, $10,000 to $15,000 for road construction), and (3) major disturbance from road construction. In addition, it is not known whether the middle aquifer is present close to the gorge.

- The middle aquifer well will be monitored during the pump test to determine leakage. If no leakage is indicated, then there will be no need for a well at Granite Gorge.
- Consensus opinion is that installation of a southern well would be of questionable value prior to the aquifer test.
- The results of the aquifer test will indicate the amount of leakage (if any) between the middle and lower aquifers. The isotopic data may also show if there is leakage.
- Any leakage (K values) found during the pump test will be applied to the entire aquifer during impact evaluation. Sensitivity runs (changing leakage rates) can be performed to model connectivity.

The issues detailed below were discussed in a subsequent hydrology team meeting. Meeting notes are as follows:

Questions had been raised regarding underflow that may be present at Granite Gorge and leakage from the lower aquifer at that point. There is no evidence to suggest that a special zone of vertical conductivity exists at the gorge. Any impacts the pumping of the lower aquifer might have would be evident near the site first. The distribution of the underflow at the gorge is not known. There is no riparian vegetation in the gorge, and that section of the river is not a gaining reach. Estimated underflow is based on Davidson's report and is assumed to be in the upper basin fill. Lakebed clays that act as the upper aquitard coarsen towards the east and west margins of the basin; they may also coarsen at the gorge. The lower aquitard seems to be volcanic clay that may be the weathered surface of the volcanic flow, and likely does not coarsen in the vicinity of the gorge.

Discharge from the lower aquifer currently appears to be to the middle aquifer and from springs. There is no surface water flow through the gorge.[1] Evidence points to a uniform vertical

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[1] This comment reflects the meeting notes. Our current understanding is that a perennial reach of the Big Sandy River does exist through Granite Gorge. This change in understanding does not affect the conclusion that no unusually conductive zone exists between the volcanic aquifer and the mouth of the gorge.

conductivity over the volcanic aquifer. A very conductive zone at the gorge will not yield the water levels obtained during the aquifer test.

Subsequently, it was agreed that two extents of the volcanic aquifer (best-estimate extent, and worst-case extent with the aquifer extended close to the gorge) be tested in the model.

These uncertain data were varied during model calibration and the most sensitive parameters tested in plant pumping sensitivity analyses. Results for all the cases are presented in Sections 3.6 and 4.0.

3.3 SELECTION OF COMPUTER CODE

The modeling approach was discussed during a hydrology team meeting, as follows:

- The team discussed using a numerical model versus an analytical model to analyze the potential impacts of pumping as part of the impact analysis.
- Joanna Moreno (URS) indicated that modern numerical models are now so easy to use that developing a simplified numerical model and an analytical model would involve a similar level of effort.
- A numerical model offers the advantage of being able to more accurately simulate boundary conditions.
- The consensus opinion is that a numerical model ultimately will be developed, although the level of complexity of the model will depend on the results of the aquifer test.

The computer code MODFLOW96 (details provided in Appendix A) was recommended by agency reviewers prior to the start of the project. This recommendation that was accepted because of the code's ability to model the key physical processes in the basin, as well as the wide successful use, peer review, and agency acceptance of the code. The version of MODFLOW96 embedded in Visual MODFLOW® version 2.8.2 build 50 (Waterloo Hydrogeologic 2000) was used for this project.

The drawbacks to using this code are that unsaturated zones at the margins of the saturated valley floor, and mass imbalances due to bending and thinning model layers, cause model instability and poor convergence. The ideal alternative, a saturated-unsaturated finite-element code, would be less easily reviewed, more time-consuming to prepare, and probably would have resulted in only marginally different results. Therefore, the selected code is appropriate.

3.4 GROUNDWATER MODEL CONSTRUCTION

The groundwater model construction is explained first by means of the geology of the area. Figure 3 shows the mapped extent of the main geologic units together with a series of cross section locations. The extent of the lakebed deposits was mapped based on the USGS facies change map (Davidson 1973) updated using information from the deep DOE exploration boring PQ25. Variations on the lateral extent of the lakebed clays were tested in the model. Figures 4A through 4F show six cross-sections (A through F, respectively) through the Big Sandy basin, predominantly through the area of the volcanic aquifer. These cross-sections include the following:

- a section through the site (A-A'); this and other sections show a thin (10-ft-thick) layer above and below the volcanic aquifer representing the aquitards that maintain the observed artesian pressures in this zone
- a section through a series of wells north of the site and running through the tip of the volcanic aquifer (B-B')
- a section through the deep DOE borings PQ10 and PQ25 showing thick deposits of lakebed clay (C-C')
- a section longitudinally along the valley extending from the deep DOE boring PQ28 in the north to PQ29 in the south, at which location volcanic rocks at least 2,000 ft thick were encountered (D-D')
- a section through Cofer Hot Spring showing how the fault that it coincides with may be a conduit for connection to the volcanic aquifer (E-E')
- a section through Granite Gorge showing one of the two volcanic aquifer extents to be modeled (F-F')

Some easterly parts of the volcanic aquifer appear to be overlain by aquitard and upper basin fill, whereas westerly parts are overlain by aquitard and lakebed clays as well as upper basin fill.

The surface topography of the basin and surrounding mountains, together with the streams and washes, is shown on Figure 5. The topography of the basin floor is gentle, but the mountains slope more steeply, particularly in the area of the volcanic outcrop in the southeast. Stream channels, only intermittently flowing, connect the mountain margins with the streambed alluvium in the center of the basin. A radial flow pattern of washes can be seen in the volcanic outcrop (southeast corner of the basin).

Figure 6 shows the water levels in the upper aquifer, as interpreted by USGS (Davidson 1973). Groundwater flow from the edges of the basin reflects mountain front recharge. This flow is toward and ultimately parallel to the Big Sandy River.

Model Grid

A three-dimensional model was used to represent the pumping and potentially impacted layers accurately. The model domain initially included the entire basin and extended to hydrogeologically well-defined boundaries. It extended from Granite Gorge in the south to the Peacock Mountains and Cottonwood Cliffs in the north. The west and east boundaries were aligned with granite outcrop locations. The northern part of the valley, furthest from the proposed power plant site, eventually was cropped from the model in order to make more model runs feasible without loss of accuracy in predictions in the main area of interest. The model domain extends from the ground surface to the deepest part of the lower basin fill, or to a depth of about 5,000 ft below ground surface.

The geology of the site was simplified into a seven-layer framework for the purpose of modeling analyses. In descending order, the layers are as follows:

- upper basin fill (upper aquifer)
- lakebed clays (where present)
- lower basin fill (middle aquifer)
- aquitard above volcanic aquifer
- volcanic (lower) aquifer
- aquitard below volcanic aquifer
- arkosic gravel

The layers all overlie essentially impermeable granitic gneiss.

The calculation grid used in the model is shown in Table 2 and on Figure 7. The orientation of the grid is at an angle to north in order to follow the main alignment of the Big Sandy basin.

TABLE 2
MODEL GRID

Cell size - x, y, z (ft)		Number of cells (columns x rows x layers)	Area (ft^2)	Thickness (ft)
Smallest (ft)	Largest (ft)			
200 x 800 x 10	2000 x 2400 x 1,700	62 x 85 x 7	1.3 x 10^{10}	5,000

Hydraulic Parameters

The distribution of hydraulic parameters in the model is presented in a series of cross sections through the model in vertical sections (Figures 9 through 11) and horizontally (Figures 12a through 12e).

The hydraulic parameters supplied to the model, together with their sources, are presented in Table 3. The initial value supplied to the model is presented as well as the final value(s) used, so that changes made during model calibration can be tracked. The primary changes made were as follows:

- Thickness of volcanic aquifer was increased as described in the following excerpt from hydrology meeting notes:

  The basic geologic concepts that had been agreed upon in other discussions are consistent with the geology represented in the model, with the exception of the change in thickness of the volcanic aquifer. Initially, it had been proposed that the volcanic aquifer was a uniformly thick flow down the surface of the granitic basement and the existing arkosic gravel deposits.

  Problems arose during the initial stages of modeling because the bottom elevation of the eastern two-thirds of the volcanic unit were significantly higher than the potentiometric surface of the aquifer as observed at the proposed power plant site. A relatively flat aquifer surface (one without steep gradients) is required to be compatible with the flux observed during the constant rate test. The extent of saturated aquifer and the volume of water available would have been reduced to levels that did not correspond to aquifer test results.

  Rather than a sloping flow across the surface from an undetermined source, the volcanic unit may be more accurately described as a volcanic vent, very thick in the center and thinning at the edges as flows across the surface. The 500 to 600 feet of volcanics initially proposed by the project proponent was a conservative estimate based on the thickness of volcanics they had drilled through during the construction of the observation wells and test holes. Evidence for a thicker unit is seen in DOE boring PQ-29, south of the proposed power plant site. The newly suggested volcanic thickness is approximately 3,000 to 4,000 ft (about 2,000 ft saturated thickness) at the proposed center of the vent (east of the proposed power plant site).

- The recharge rate to the volcanic aquifer was reduced and the recharge from the mountain front recharge increased correspondingly, such that the predicted confined heads in the volcanic aquifer matched the observed heads.

- The hydraulic conductivities in the arkosic gravel were reduced so that the overall flow balance in the valley matched inflows and outflows reported by USGS (Davidson 1973) and updated in this report.

- Other input data remained as initially estimated. The model calibration process is described in Section 3.5.

Boundary Conditions

The distribution of recharge supplied to the model is shown on Figure 13. It consists of mountain front recharge along the base of the mountains, and infiltration in the permeable volcanic aquifer outcrop area. The mountain-front recharge rates greatly exceed the outcrop area recharge rates because mountain-front recharge reflects recharge from the upgradient granite uplands, whereas outcrop recharge reflects a fraction of incident precipitation.

The distribution of evapotranspiration, springs, and pumping wells is shown on Figure 14. Evapotranspiration was distributed by vegetation type along the riverbed. An extinction depth (maximum root depth) of 50 ft was assumed. However, ground surface elevations on a 100-meter grid were supplied to the model, introducing some inaccuracy to point elevations. So, the rates of evapotranspiration were adjusted by a uniform factor until the predicted and expected evapotranspiration rates matched. There are a series of small springs mapped by the BLM around the margin of the volcanic outcrop and in the surrounding granite area, or in washes nearby. The locations of these springs, which are not connected to the valley aquifer flow regime, as well as the major spring, Cofer Hot Spring, are shown on Figure 14. The proposed pumping well locations also are shown on this figure.

TABLE 3
MODEL INPUT DATA RANGES

Parameter	Reported Range	Initial Model Input Value	Base Case Model Input or Output Value	Source
Regional ground water elevations (ft NGVD29):	1,700 - 5,000	1,700 – 5,000	1,900 - 5,000	Davidson (1973)
Aquifer and aquitard thickness (ft):				
Upper Basin Fill and Stream /Floodplain Deposits	0 - 200	0 – 200	0 - 200	ADWR Drill Logs
Big Sandy Formation lacustrine clay	0 - 3,400	0 - 3,400	0 - 3,400	DOE Drill Logs
Lower Basin Fill	0 - 3,000	0 - 3,000	0 - 3,000	Inferred from Cross Sections
Basalt Aquiclude	10	10	10	Caithness/Manera (2000)
Volcanic Aquifer	300 - 500	300 – 500	300 - 4,000	Caithness (2000),Davidson (1973)
Arkosic Gravel	0 - 3,000	0 - 3,000	0 - 3,000	Caithness (2000),Davidson (1973)
Infiltration from meteoric recharge (in/y):				
Recharge along mountain fronts (30% of Tbl surface area)	Net 5% precipitation	2.8	6.5	Basin-wide recharge based on Maxey-Eakin data for the relevant elevations (Wilson and others, 1980) and checked versus water budget (Davidson, 1973 updated in DEIS). Distribution of recharge was varied during modeling analyses.
Recharge to volcanic outcrop (100% of Tv surface area)		2.8	1.35	
Groundwater pumpage and other outflows (gpm):				
Bagdad Mine (1,900 – 2,005 af /yr)	1,178 - 1,243	1,200	outside domain	Cady (1980)/USGS 1990 Water Use Rpt
Big Sandy Energy Project (40 years)	3,000	3,000	3,000	Caithness (2000) PWs 2,4,5,6
Evapotranspiration (gpm):				
Saltcedar 2.3 – 4.0 (ft/yr) (1254 ac)	1,788 – 3,109	5,300 – 10,116	8,491	Lines (1999) Ref:Ball et al (1994), Hansen et al.,1972
Mesquite 1.4 – 4.0 ft/yr (889 and 2658 ac)	3,078 – 8,794			Lines (1999) Ref:Ball et al (1994), Hansen et al.,1972
Cottonwood/Willow 4.1 ft/yr (167 ac)	424			Lines (1999) Ref:Ball et al (1994), Hansen et al.,1972
Outflows at springs (gpm):				
Cofer Hot Spring	20 176	model output	498	Davidson (1973) Manera/Caithness (measured 2000)
Other springs in model domain	7	model output	not in same flow regime	Lin Fehlmann (BLM) mostly measured in 1991, lower flow rates generally observed during isotope sampling (2000)
Evaporation and Evapotranspiration at marsh near Denton Well (gpm)	1,893	Model output	5,714[2]	Evaporation and evapotranspiration from 335 acre marsh (area based on USGS quad)
Flow in Big Sandy River - downstream side of Granite Gorge (4.533 cfs) (this number may include underflow)	2,034	model output	flow and underflow: 965	BLM (1994 - 2000), site B1, segment C of Big Sandy River below Granite Gorge
Underflow at Granite Gorge (800 ac-ft/yr)	496 -505	model output		Davidson (1973)
Horizontal Hydraulic Conductivity (ft/d):				
Upper Basin Fill and Stream /Floodplain Deposits (T = 13,000 - 20,000 ft^2/d)	265 - 335	300	300 (streambed) 100 (UBF)	Davidson (1973)(pg 32)

[2] A case with lesser evaporation rates was also tested. It is reported in Section 4.2 and Table 9.

TABLE 3
MODEL INPUT DATA RANGES
(continued)

Parameter	Reported Range	Initial Model Input Value	Current Model Input or Output Value	Source
Big Sandy Formation lacustrine clay (0.0003-0.01 gpd/ft ^{2})	0 - 1 x 10^{-5} 4.0 x 10^{-6} - 1.3 x 10^{-3}	1.0 x 10^{-4}	1.0 x 10^{-4}	Trauger (1972) Morris & Johnson (1967) (clay)
Lower Basin Fill (T = 1,300 - 6,700 ft2/d; b = 94 - 188 ; Sp. Cap. = 10 - 20 gpm/ft)	6.9 - 71.3	30	5	Davidson (1973)(pg 32)
Basalt Aquiclude	---	1.0x10^{-4} - 1.0x10^{-6}	5.0x10^{-4} 1.0x10^{-5}	calibrated based on observed responses to pumping
Volcanic Aquifer (T >1.0x10^{6} gpd/ft; b = 500 -2,100 ft)	>63	500	150 (fractures) 10 (blocks) 50 (uniform k)	Schafer (2000)
Arkosic Gravel (sp. Cap. = 10 gpm, b = 81 - 295 ft)	6.53 - 23.77	15	0.01	Davidson (1973)(pg 19)
Vertical Hydraulic Conductivity (ft/d):				
Upper Basin Fill and Stream /Floodplain Deposits	50% of horizontal	150	30	Morris & Johnson (1967) (coarse sand)
Big Sandy Formation lacustrine clay (2.1x10^{-7} - 3.0x10^{-8} m/s)	50% of horizontal	5.0x10^{-5}	1x10^{-6}	Morris & Johnson (1967) (clay)
Lower Basin Fill	same as horizontal	30	1	Morris & Johnson (1967) (medium sand)
Basalt Aquiclude	same as horizontal	1.0x10^{-4} - 1.0x10^{-6}	5.0x10^{-4} 1.0x10^{-5}	assumed
Volcanic Aquifer	same as horizontal	500	150 (fractures) 10 (blocks) 50 (uniform k)	assumed
Arkosic Gravel	50% of horizontal	7.5	0.001	Morris & Johnson (1967) (gravel)
Storativity (1/ft):				
Upper Basin Fill and Stream /Floodplain Deposits (4.9 - 10)x10-4 1/m	(2 - 3)x10^{-4}	2.0x10^{-4}	2.0x10^{-4}	Domenico (1972) (loose sand)
Big Sandy Formation lacustrine clay (9.2 - 13)x10-4 1/m	(3 - 4)x10^{-4}	2.0x10^{-4}	2.0x10^{-4}	Domenico (1972) (medium clay)
Lower Basin Fill (1.3-10)x10-4 1/m		2.0x10^{-5}	2.0x10^{-5}	Domenico (1972) (sand)
Basalt Aquiclude	same as volcanic aquifer	2.0x10^{-6}	2.0x10^{-6}	assumed
Volcanic Aquifer (storage coefficient 4x10^{-4} - 2x10^{-3},b=850 ft in area of PW 2)	5x10^{-7} to 1.4x10^{-6}	2.0x10^{-6}	1.0x10^{-6}	Schafer (2000)
Arkosic Gravel (4.9 - 10)x10^{-5} 1/m	(2 - 3)x10^{-5}	2.0x10^{-5}	2.0x10^{-5}	Domenico (1972) (gravel)
Effective Porosity:				
Upper Basin Fill and Stream /Floodplain Deposits	0.15	0.15	0.15	Davidson (1973)
Big Sandy Formation lacustrine clay	0.10	0.1	0.1	Davidson (1973)
Lower Basin Fill	0.32	0.32	0.32	Morris & Johnson (1967) (medium sand)
Basalt Aquiclude	0.01 - 0.17	0.1	0.1	Morris & Johnson (1967) (clay)
Volcanic Aquifer	0.05 - 0.17 0.04 - 0.09	0.07, 0.11, 0.15	0.11	Singhal & Gupta (1999) Trauger (1972) (vesicular basalts of New Mexico)
Arkosic Gravel	0.21 - 0.28	0.25	0.15	Morris & Johnson (1967) (gravel)

The model domain and boundary conditions, other than those presented on Figures 13 and 14, are shown on Figure 15. These boundary conditions are as follows:

- no flow boundaries at the margins of the basin and either side of Granite Gorge
- constant head boundary at the northern edge of the model representing inflow from recharge to the northern part of the basin, outside the active modeling domain
- wall boundary around the outside edge of the volcanic aquifer representing part of the aquitard observed to maintain the artesian pressures in this aquifer
- drain at Cofer Hot Spring representing connection via a fault to the volcanic aquifer
- general head boundary at the marsh near the Denton well representing evaporative losses to groundwater and surface water
- general head boundary at Granite Gorge representing subsurface outflow via the gorge

Initial Conditions

The initial conditions supplied to the model were an approximation of the observed hydraulic heads in the upper aquifer. When transient runs were made, a steady state run was first completed to provide mass-balanced initial conditions (heads).

Simplifying Assumptions

Three simplifying assumptions, other than those already discussed, were used in the modeling analysis, as follows:

(1) An aquitard is assumed to exist as a skin around the volcanic aquifer. This aquitard is assumed to have uniform thickness and properties. This assumption is consistent with the aquitard observed in several wells. The aquitards confining the volcanic aquifer are known to be competent because of the 175-ft head drop observed across this interface. This assumption also is based on the results of the aquifer test analyses that demonstrated that the lower aquifer is hydraulically isolated from the middle and upper aquifers over the area monitored. This assumption was tested by varying the hydraulic properties assumed for the aquitard. These tests showed that a more transmissive aquitard was inconsistent with both the observed vertical hydraulic gradients and the observed lack of response in the middle aquifer during the aquifer pumping test.

(2) The volcanic aquifer was assumed to be a uniform porous medium. A block and fracture system in this aquifer was identified by the aquifer test analyses. This assumption was tested by analyzing long-term pumping using both a fracture and block approximation, and a uniform hydraulic conductivity approximation, for the volcanic aquifer. The predicted long-term drawdowns were almost identical. These data are presented in Section 3.5.2.

(3) A uniform pumping rate was applied at the four proposed pumping well locations. In practice, operation of the wells will rotate, with a uniform overall rate of discharge. The wells are sufficiently close to each other that this assumption is not expected to affect any modeled results.

(4) Model inflows and outflows of less than 1 percent of the basin inflows or outflows were neglected in the model.

Model Limitations

The calibrated model is limited to, and has been tuned to, the simulation of pumping in the volcanic aquifer and its effects on the water levels and water budget of the lower half of the Big Sandy basin. Although conservative estimates have been tested in the model sensitivity analyses, unmapped geologic features could change the actual impacts. The assumptions used in the model have been discussed in the previous sections. The likely effects of the main assumptions on the predicted impacts due to pumping are as follows:

- Geology and size of volcanic aquifer: A different extent of volcanic aquifer than modeled would result in a different distribution of projected impacts. A smaller aquifer extent than modeled would result in a greater impact due to pumping on drawdowns in the volcanic aquifer, and less impact due to pumping in the upper aquifer (more fractional coverage by the lakebed clays). A larger aquifer extent than modeled would result in a lesser impact due to pumping on drawdowns in the volcanic aquifer, and more impact due to pumping in the upper aquifer (less fractional coverage by the lakebed clays). So, these two effects tend to offset one another since drawdowns in the volcanic aquifer are directly related to impacts in the middle and upper aquifers. One scenario tested, that of a volcanic aquifer extended to the vicinity of Granite Gorge, resulted in unrealistic head distributions (Section 3.6). The modeled aquifer extent is consistent with the aquifer pumping test analysis conclusions (David Schafer & Associates 2000). Simulation of fractures and blocks rather than an equivalent porous medium was tested and found to have little effect on projected impacts (Section 3.5.2). A fracture zone is believed to connect Cofer Hot

Spring with the volcanic aquifer, resulting in artesian flow. If other, similar fractures existed, then project pumping would reduce outflows and possibly induce inflows via these fractures. However, any fractures connecting to ground surface elevations less than 2,084 ft (the head in the volcanic aquifer) would produce other artesian springs; such springs have not been observed. Fractures connecting the volcanic aquifer to ground surface elevations above 2,084 ft would not be connected to the upper aquifer because it does not exist along the valley margins. Fractures connecting the volcanic aquifer to the middle aquifer for ground surface elevations above 2,084 ft would be isolated from the upper aquifer by the lakebed clays.

- Specific yield of volcanic aquifer: Greater or lesser specific yields in the volcanic aquifer than modeled would result in lesser or greater impacts due to project pumping in all three aquifers, respectively. The range of specific yields presented in the literature, consistent with the observed volcanic aquifer hydraulic properties, was tested and found to affect predicted impacts due to project pumping by a factor of 50 percent (Section 4.0). The worst-case results are presented in Sections 3.6 and 4.0. Specific yields outside this range may exist locally and would cause local variations in projected impacts.

- Hydraulic conductivity of aquitards confining volcanic aquifer: Greater or lesser aquitard conductivities than those modeled would lead to greater or lesser impacts due to pumping, respectively. However, the aquitards confining the volcanic aquifer are known to be competent because of the 175-ft head drop observed across this interface. A range of aquitard conductivities was modeled and only a relatively narrow range of values produced predicted hydraulic heads and vertical gradients similar to those observed. The results for these cases are given in Section 4.0.

- Recharge rate at outcrop of volcanic aquifer: Greater or lesser recharge rates into the volcanic aquifer outcrop than those modeled would result in (1) a greater or lesser impact due to pumping on the upper two aquifers, respectively, and (2) a lesser or greater impact due to pumping on the volcanic aquifer than modeled, respectively. However, there is a realistic limit to the level of aquifer recharge that is likely to occur in this area of 12 in/yr precipitation. Levels of two to three times the likely recharge rate (based on the Maxey-Eakin method of assigning recharge by elevation) were tested (Sections 3.6 and 4.0).

- Groundwater flow to marsh: The groundwater outflow at the marsh and through the Granite Gorge as underflow and/or streamflow are linked in that the basin water budget is balanced if changes in these two outflow components offset one another. At different times of the year the balance between these two components may vary, and also differ from that modeled. Both sets of outflows are modeled and reported separately. An alternate combination of outflows (less outflow from the marsh and more through Granite Gorge) was tested and is reported in Section 3.6.

The model was tested with respect to observed current hydraulic heads in the three aquifers and observed responses during pumping. Many cases were rejected as being insufficiently accurate. A range of cases covering best-estimate and upper and lower limits for those parameters most sensitive to predicted impacts were evaluated and are presented later in this report. The model input data and assumptions that resulted in the best match to observed flows and heads were used in evaluating the likely effects of project pumping.

3.5 MODEL CALIBRATION

This section presents the calibration information that demonstrates the level of agreement between the predictions from the Big Sandy basin model and field data. The calibration information provided uses ASTM modeling guidance (ASTM 1993, 1994, and 1995) and EPA quality assurance/quality control (QA/QC) guidance (EPA, 1992) as checklists for material presented.

The purpose of model calibration is to obtain reasonable estimates for uncertain model input data, such that model predictions match observed data to the degree possible given groundwater conditions and the distribution of field data.

Model calibration usually involves the following steps:

- Specify calibration criteria and calibration protocol. Calibration criteria compare model-prediction errors with key components of the model mass balance. That is, a discrepancy between predicted and observed heads is compared to a key hydraulic gradient, and/or observed variability in heads. Model performance criteria can be tested by comparing predicted and observed values for corresponding locations in time and space. Common examples of such testing are as follows:

  - root mean square error between predicted and observed data should be less than about 10 percent of the range of observations

  - bias between predictions and observations should be random rather than systematic.

- Modify model assumptions and/or uncertain input data, within reasonable bounds, to obtain a realistic simulation.

- Evaluate the model predictions versus observations. The model evaluation should use as many pieces of information as possible (i.e., not just water levels, but also spring levels, river inflows/outflows, vertical hydraulic gradients, and any other relevant descriptive data)

- Examine "calibrated" model input and output and evaluate whether the following are true:
  - input data individually and jointly make sense
  - site-specific data cover the area predicted to be of concern
  - model output indicates initial conceptualization was appropriate

Model calibration is presented in two sections: steady state calibration results and transient calibration.

Steady State Calibration

Current conditions were used to calibrate the model. Groundwater levels, basin-wide flow balance, spring discharge rates, river discharge rates, and responses to pumping were used to assess the validity of the calibration.

Calibration Targets

Calibration targets are field-measured quantities, such as heads and flow rates, that can be used to evaluate the model calculations. These targets are subject to error in that they vary with time, and are measured at locations that do not coincide with model calculation nodes. The calibration targets for the Big Sandy basin model are the 63 measured heads in the upper aquifer and data from the 11 wells monitored in the three aquifers adjacent to the proposed power plant site. Also, the main components of the water balance were used to assess the accuracy of model-predicted flows.

In addition, calibration criteria based on the degree of correlation between predicted and observed heads were established. This calibration goal was that the root mean square error should be less than 10 percent of the observed range of heads. The observed range of heads is about 917 ft.

Calibration Process

Calibration was achieved through variation of hydraulic conductivities of the hydrogeologic units within reported ranges, and variation of infiltration rates such that the sum of the recharge was equivalent to about 5 percent of the precipitation rate, in a set of more than 50 test calculations. The mean error between predicted and observed heads for each of the 74 observed locations was used to assess each subsequent run, and the best calibrated run was selected to be the model run that accomplished the following:

- minimized the mean error between predicted and observed heads
- matched the expected flow rates through Granite Gorge reasonably well
- matched observed vertical hydraulic gradients between the three aquifers near the proposed power plant site
- satisfied the calibration criterion
- was well balanced and conserved mass

Calibration Results

The calibration results are presented both qualitatively and quantitatively. Figures 16 to 19 show the predicted hydraulic heads in each of the three aquifers and in a vertical cross-section through the site. Figure 20 shows the location of the calibration datapoints illustrated in the scatter diagrams on Figures 21 and 22. Figure 21 shows all of the observation data. On this figure it should be noted that the data are taken from a time period covering 1959 through 1970. The data are therefore not a consistent data set. Figure 22 shows data from the wells monitored in 2000, close to the proposed power plant site. The data for the wells in the lower volcanic aquifer are shown in the top right-hand corner, the data for the middle aquifer are in the middle of the graph, and the data for the upper aquifer are in the lower left-hand corner. Considering both graphs, on average the predicted and observed heads differ by 13 ft (with mean absolute error of 39.9 ft). The residuals are not biased (the mean error being close to zero) and are not spatially biased, other than due to the distribution of data.

The correlation between the predicted and observed data are also presented using the following measure of model error:

Root mean square error (RMSE):

$$RMSE = \left[\sum_{i=1}^{n} \frac{(P_i - O_i)^2}{n} \right]^{1/2} \left[\frac{100}{\bar{o}} \right]$$

where: O = observed value

P = predicted value

n = number of values

= mean of the observed values

RMSE tends to zero for perfect predictions.

The RMSE was calculated to be 52 ft. Since the RMSE is less than 10 percent of the observed range of heads (917 ft), the quantitative calibration goal was met.

In addition, the predicted flow rates for the main components of the flow balance match the expected rates, as shown in Table 4.

TABLE 4
PREDICTED VERSUS ESTIMATED COMPONENTS OF WATER BALANCE

	Predicted Flow Rate		Estimated Flow Rate*	
Flow Component	**gpm**	**ac-ft/yr**	**gpm**	**ac-ft/yr**
Recharge	15,380	24,800	17,522	28,262
Evapotranspiration	9,195	14,830	5,300 - 10,116	8,548 - 16,316
Evaporation and Evapotranspiration from Marsh**	5,714	9,210	1,893	3,053
Outflow at Granite Gorge	965	1,556	496 - 2,034	800 – 3,280
*From Tables 1 and 3. **A case with lesser evaporation rates was also tested. It is reported in Section 4.2 and Table 9.				

Predicted and observed hydraulic head drops between the three aquifers also were compared, as shown in Table 5.

TABLE 5
PREDICTED VERSUS OBSERVED HYDRAULIC HEADS AND HEAD DIFFERENCES IN THE THREE AQUIFERS

Monitor Well and Aquifer	Observed Head (ft amsl)	Predicted Head (ft amsl)	Observed Head Difference (ft)	Predicted Head Difference (ft)
Lower Aquifer OWC2	~2084	2097		
Middle Aquifer OWMA2	1909	1906	175 120	191 82
Upper Aquifer OW8	1789	1824		

Based on all of these criteria, the model was judged to be sufficiently well-calibrated for use in predictions of future conditions in the valley.

As a result of examining the predicted hydraulic heads along various cross-sections (e.g., the cross-sections shown on Figures 23 through 25), the relationship between the wells and springs upgradient of the proposed power plant site and the basin flow system was illustrated. Figure 23 shows a vertical cross-section through Rincon Wells A and B. The locations of the wells and springs on Figure 23 and the following figures are indicated on the right-hand (east) side of the cross-section. The observed water level elevation in the wells and springs is shown by a small blue line, and the ground surface elevation shown is surface topography averaged on a 100-meter grid. The observed hydraulic head in the volcanic aquifer is shown as a solid blue line. Given the high transmissivity of the volcanic aquifer, and the relatively low recharge rates in its outcrop area, this line is essentially flat (heads are uniform). Figures 23 through 25 show that the wells and springs upgradient of the proposed power plant site and close to the volcanic outcrop have heads 1,000 ft offset from that of the volcanic aquifer. This shows that these springs and wells are probably in separate, shallow flow systems and would be unaffected by power plant pumping.

Discussions in the hydrology team meetings regarding calibration results were as follows:

The springs and wells to the east of the proposed power plant site have water level elevations that are about 1,000 ft higher than water levels in the volcanic aquifer. These are likely separate flow systems from the confined aquifer, issuing from perched aquifers in the granite, and will not be affected by pumping.

The springs are located at the edge of the volcanic aquifer. Isotope analysis indicates that while Cofer Hot Spring probably has the same source of water as does the confined aquifer, the springs in the Aquarius Mountains are more meteoric in nature. During the collection of isotope samples, it was noted that flows in the sites visited were reduced about 10-fold from 1991 measurements made by BLM personnel, suggesting that spring flow rates are variable.

Transient Calibration

A transient calibration was undertaken using the aquifer test data. Predicted drawdowns during the pumping and recovery phases of the aquifer test were used to evaluate the model. Steady state (non-pumping) heads were used as model initial conditions for the runs described in this section.

Due to the unusual response of the wells in the pumped aquifer (all wells had similar responses), several methods of representing the volcanic aquifer were tested, as follows:

- uniform conductivity, confined aquifer
- uniform conductivity, confined/unconfined aquifer
- fracture and block model

The optimal aquifer properties assumed in each case are listed in Table 6.

TABLE 6
MODEL INPUT PARAMETERS FOR VOLCANIC AQUIFER TEST SIMULATIONS

Parameter[a]	Observed Range	Fracture and Block Model	Confined Uniform Hydraulic Conductivity Model	Unconfined Outcrop Model
Hydraulic Conductivity[b] (ft/d)	> 63	10 (blocks) and 150 ft/d (fractures)	50	50
Specific storage[c] (1/ft)	5×10^{-7} to 1.4×10^{-6}	1×10^{-6}	6×10^{-7}	1×10^{-6}
Specific yield	-	0.00085	0.0005	0.00085 (confined zone) and 0.09 (outcrop area)

[a] Net recharge to the volcanic aquifer, when modeled as an isolated layer, is assumed to be zero.
[b] Conductivity is based on a transmissivity > 1.0×10^6 gallons per day per foot (gpd/ft) and a saturated thickness ranging from 500 ft to 2,100 ft
[c] Specific storage is based on the storage coefficient of 4×10^{-4} to 2×10^{-3} and an average saturated thickness of 850 ft near PW2

A one-layer model subset of the Big Sandy model was used for these tests and then the seven-layer model was applied to verify the conclusions. The block and fracture geometry tested is illustrated on Figure 26, together with the pumping and observation well locations. Figures 27 through 29 show simulated and observed drawdowns at the wells more distant from the pumping center for each of the assumed volcanic aquifer properties. Since the volcanic aquifer was simulated in total isolation from its surroundings for these tests, the recovery tails of the drawdown curves are not necessarily accurate representations of purely the effects of pumping, but also of the model reaching a new equilibrium. However, based on the peak drawdowns and the shape of the drawdown curves predicted the following conclusions were made:

- The fracture and block model gives the best match to observed drawdowns at the wells distant from the pumping center.

- The drawdown at the pumping well is best matched by the confined/unconfined model, but not well matched by any model (note: in the aquifer test analysis report drawdown at the pumping well was ignored in calculating relevant aquifer parameters)

A sensitivity analysis for the block and fracture model was run with 10-fold increased transmissivity in the fracture zones. The results of this case are shown on Figure 30. It can be seen that the pumping well and observation well drawdowns are all matched in this case, but that the drawdown curves are poorly matched.

The 10-day pumping test was simulated with the base-case seven-layer model, except that confined conditions were assumed throughout the aquifer during the test (this is how the aquifer responded for short-term pumping). The results of this simulation are presented on Figure 31, which also shows the one-layer model base-case results and the 1-layer model fracture and block case for comparison.

In the seven-layer case tested, the predicted drawdown in the middle and upper aquifers was negligible and the combination of parameters agreed well with the observed steady state heads.

It can be seen that the following occurred for simulated heads at Observation Well 3 (OW3) (more typical of the aquifer in general than OWC2):

- the seven-layer model simulated the aquifer pumping test better than the one-layer model, with conductivity assumptions being equal.

- the fracture/block model matched the pumping test data best

- the original base-case best matches steady state and transient heads

In conclusion, the uniform conductivity model was used in the basin model, and the block and fracture model was used in the single-layer model, to evaluate long-term pumping (Figure 32). The predicted drawdowns from the two models were similar, suggesting that either approach could be used in the full-scale basin model. Since the uniform hydraulic conductivity model required many fewer model cells without loss of accuracy, this approach was chosen for the remaining model runs.

3.6 SENSITIVITY ANALYSES

The sensitivity analyses were conducted to evaluate the following:

- if alternate conclusions about impacts could be drawn from an alternate, equally valid model
- which are the most sensitive of the uncertain model parameters
- the range of results considering uncertain parameters
- likely accuracy of model results

The following uncertain input parameters key to the analysis of impacts were identified in hydrology team meetings:

- aquitard hydraulic properties
- specific yield of volcanic aquifer
- extent of volcanic aquifer near Granite Gorge

In addition, three other parameters were tested when they were found to affect predicted impacts:

- The effect of assuming different lateral extents for the lakebed clay unit was assessed. It was found that reducing the lateral width of the lakebed clay deposit in the model, which increases the degree of connection between the middle and upper aquifers, resulted in decreasing the predicted hydraulic gradient between the middle and upper aquifers, resulting in a mismatch with observed heads.
- The effect of different recharge rates into the volcanic aquifer (1.35 to 1.85 in/yr) was tested in conjunction with the aquitard hydraulic conductivity tests. It was found that recharge rates greater than 1.6 in/yr led to inaccurate hydraulic gradients between the volcanic and middle aquifers.

- The effect of a three-fold smaller assumed evaporation rate at the marsh was investigated. It was found that this change affected the relative flow rates through the marsh and gorge and the predicted drawdowns resulting from pumping. The results are provided in Section 4.2.

Also, The effect of assuming a larger extent of lakebed clay, including the entire area beneath the marsh, was tested. It was found that the predicted drawdowns and reductions in flow rates due to pumping were unchanged as a result.

3.6.1 Steady State Hydraulic Heads

Each of the sensitivity case parameters was varied individually. The results were then compared to field data to see whether the results were realistic. Comparing predicted and observed heads under non-pumping conditions shows that, statistically, the extended aquifer case is infeasible (Table 7). This is because the gradient between the end of the volcanic aquifer and Granite Gorge was too high to allow the observed heads in the volcanic aquifer to be maintained. The aquitard conductivity of $1x10^{-4}$ ft/d case also was infeasible, because the confined aquifer pressures were released. The volume of additional recharge that would be required to redress the balance is infeasibly high. However, an intermediate case in which aquitard conductivities and outcrop recharge rates were increased jointly was found to be feasible and is reported below. Higher infiltration rates and aquitard conductivities than this also were tested but resulted in an unrealistic reduction in the predicted head difference between the volcanic and middle aquifers. In addition, the increased recharge rate of 1.6 in/yr required for this case is two to three times higher than the average recharge rate. This recharge rate already may be unrealistically high for direct infiltration and even higher rates are judged to be unrealistic.

TABLE 7
CORRELATION BETWEEN PREDICTED AND OBSERVED HEADS FOR SENSITIVITY CASES

Statistical Correlation	Base Case	7% specific yield case	15% specific yield case	Aquitard conductivity of $1x10^{4}$ ft/d	Aquitard conduct-ivity of $4x10^{-}$ ft/d*	Aquitard conductivity of $1x10^{6}$ ft/d	Volcanic Aquifer extended to Granite Gorge
RMSE (all wells) (%)	5.7	5.7	5.7	23.2	5.7	5.7	10.6
RMSE (site wells) (%)	7.3	7.3	7.3	123	7.3	10.7	64.5
Conclusion	Feasible solution	Feasible solution	Feasible solution	Infeasible solution	Feasible solution	Feasible solution	Infeasible solution

Storativity of 1 x 10^{-6} ft^{-1} used in all cases.
*Volcanic outcrop recharge rate increased from 1.35 to 1.6 in/yr.

3.6.2 Transient Hydraulic Heads

An aquifer test was conducted in the volcanic aquifer and monitored in the middle and upper aquifers. These data were used to confirm the model predictions. In all of the cases presented in this section, steady state (non-pumping) heads were used as the model initial conditions. Continuing with the feasible model cases (Table 8), most of the sensitivity analyses produced results consistent with the aquifer test results. This is because the unconfined aquifer parameters are not tested in a 10-day pumping test; it was predicted that more than 10 years of pumping are needed to distinguish between the reality of the assumed input parameters. The case with an aquitard conductivity of 4×10^{-5} ft/d and increased volcanic aquifer recharge did show a small drawdown in the middle aquifer where none was observed during the aquifer test, so this value for the aquitard conductivity probably is the upper limit of realistic values. Consequently, all five feasible cases were investigated further. The remaining sensitivity cases are presented with the predicted results for ease of understanding model prediction accuracy.

TABLE 8
PREDICTED AND OBSERVED DRAWDOWNS FOR SENSITIVITY CASES

Monitored Location	Observed Drawdown (ft) after 10 Days of Pumping at 1,960 gpm	Predicted Drawdown (ft) after 10 days of Pumping at 3,000 gpm				
		Base Case	7% specific yield case	15% specific yield case	Aquitard conductivity of $4x10^{-5}$ ft/d	Aquitard conductivity of $1x10^{-6}$ ft/d
Volcanic Aquifer (OWC2)	7.5 - 8.0	7.3	7.5	7.2	7.3	7.4
Middle Aquifer (OWMA2)	0.0	0	0	0	0.01	0
Upper Aquifer (OW8)	0.0	0	0	0	0	0
Upper Aquifer (Banegas Ranch well)	0.0	0	0	0	0	0
Conclusion	-	Feasible solution	Feasible solution	Feasible solution	Feasible solution	Feasible solution

Storativity of 1×10^{-6} ft^{-1} used in all cases.